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Modular assembly is being applied to an increasing number of vehicles and part manufacturers to manage the ever-changing demands of the automotive industry. In spite of many researches performed on the supply chain management and logistics aspects of modular production, there is no research discussing modular production line concepts used by module suppliers. In this paper, labour productivity of two assembly line concepts including the conveyor line and box assembly line is studied under modular production environment. Both line concepts and respective assembly processes are described in detail. Mathematical models showing the total work faced by these two assembly line concepts are developed and compared. Two productivity scales are defined: the maximum achievable productivity and the actual productivity. The labour productivity rates of these assembly line concepts on above productivity scales obtained from calculations and a simulation are compared as a performance measure.

Keywords: modular assembly; synchronous production; labour productivity; box assembly line; conveyor line

1. Introduction

In recent decades, the automotive industry has been transitioning from mass production to mass customisation. One of the main reasons behind this is stated in the literature (Starr 1965; Helper, MacDuffie, and Sabel 2000; Calcagno 2002) as the increasingly complicated customer demands requiring highly diversified products. These products are being introduced to the market faster than ever and in the most cost-efficient way possible for companies to survive in this fiercely competitive environment. As a result, car manufacturers (Original Equipment Manufacturers; OEMs) and their suppliers have been seeking innovative ways of coping with the changing environments of the industry through more flexible and efficient processes. In this regard, modules are perceived to be an engineering tool for companies to manage a complex product by dividing it into sub-assemblies. Modular production is being applied by an increasing number of vehicles and part manufacturers to deal with the new orders of the industry.

Sako and Warburton (1999) defined a vehicle module as ‘a group of components, physically close to each other that are both assembled and tested outside the facilities and can be assembled very simply onto the car’. Modularity was initiated as an engineering concept and applied as a design principle by car makers. Vehicle manufacturers believe that further gains can be achieved by outsourcing some of the modular activities to suppliers. Currently, a car is divided into a number of modules assembled at different stations of the vehicle assembly line. Common modules used in the automotive industry include the cockpit, front-end, seat, door, fuel tank, etc. (McAlinden, Smith, and Swiecki 2000). These modules require hundreds of components with different variants to be assembled. Therefore, material procurement, purchasing and assembly of these different parts are complex processes that suppliers seek to manage in the most possible productive way. Modular production methods have also begun to play important roles in automotive manufacturing due to the increasing application of the modular concepts in vehicles. Some OEMs assemble modules on their vehicles in-house by either their workforce or outsourced labour, whereas other OEMs outsource the total module structure itself to vendor companies located outside their premises. A combination of these strategies is also possible, where some modules are assembled by the OEM and some are outsourced to vendor companies.

Modular production is a complex problem involving manufacturing and logistics systems, as well as overall supply chain management. Although there is research on the supply chain management (Sako 2003) and logistics (Fredriksson 2006) of modular production, there is no research discussing modular production line concepts used by module suppliers. This paper examined two modular assembly line concepts used by two front-end module suppliers: the conveyor line and box assembly line. The conveyor line is a very common assembly line concept in the automotive industry that

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*Corresponding author. Email: kyryu@pusan.ac.kr is used by many module suppliers as well. It is a flow-oriented production system and often consists of serial assembly stations connected by conveyors (Boysen, Fliedner, and Scholl 2008). As indicated by Scholl (1999), assembly lines were developed for mass production of standardised products originally. Since the stations are connected, it is highly efficient for flow of materials and units (Yamada, Satomi, and Matsui 2006). Two major drawbacks of the conveyor line include low flexibility with respect to changes in demand and/or product design and loss resulting from imperfect line balance (Bukchin, Darel, and Rubinovitz 1997).

Recently, manufacturing cells are gaining popularity in the manufacturing industry as it has been shown that they reduce lead time and work-in-process inventory while improving product quality and response time to customer orders (Suer and Tummaluri 2008). As a type of cellular manufacturing, the box assembly concept has also gained attention and is claimed to be more flexible than the conveyor line since it offers routing flexibility as well as resource pooling (Johnson 2005). If the volume is higher than expected, additional assembly boxes that are already developed can be constructed easily at relatively low cost. Other benefits include allowing separate maintenance actions on assembly boxes, and enabling better labour evaluations due to clear work separation, thereby encouraging higher work quality and higher performance. When modular production considered, major drawbacks of this concept include the additional efforts required for module sequencing work and multiple handling of the module components. While most of researches so far show that assembly cells outperform conveyor lines, it is claimed that there are manufacturing environments where conveyor lines are better to implement (Sengupta and Jacobs 2004; Johnson 2005). Although a comparison between these two concepts has been an interesting issue for industrial managers of module suppliers, it is difficult to judge which concept is better for modular production. As mentioned previously, both concepts have their advantages and disadvantages. The line concept, in which the module company and workers have been working with, also matters due to learning effect. Therefore, this study examined these two assembly line concepts under modular production environment by developing their corresponding mathematical models, which are used to compare their respective labour productivities as a performance measure.

2. Related research

2.1 *Modularity and synchronous production*

The transition of the automobile industry from mass production to mass customisation is based on the need to produce more customised vehicles and provide many variants using fewer resources and materials in the shortest time possible (Chryssolouris, Papakostas, and Mavrikios 2008). A common automotive assembly line allows car manufacturers to produce a wide variety of platform models on a single production line, and is therefore a mixed model assembly line. Kim and Jeong (2007) characterised mixed-model assembly lines according to their ability to assemble different models of a given product without holding large inventories. A car is composed of approximately 20,000 components (Alford, Sackett, and Nelder 2000), meaning that vehicle manufacturers face a large burden when meeting the diverse demands of their customers. Product modules offer car manufacturers the ability to use efficient mass customisation by enabling the postponement of a product's final assembly until customer orders have been received (Fredriksson and Gadde 2005). Modular design leads to modular assembly, meaning that the sub-assembly of components leads to product modules. Each module has a unique flow, and is assembled and delivered in sequence to the final assembly line (Fredriksson 2002).

One of the distinctive characteristics of modularity is synchronous production, which was defined by Doran (2002) as an integrated supply chain approach that ensures the delivery of defect-free products that match the exact production requirements of the customer. These products reflect the precise variations of the designated vehicle and are delivered to the appropriate assembly location within a given time frame (see Figure 1). The production line of module suppliers is well synchronised with that of the customer, meaning that there is one-to-one correspondence between the products assembled in the two lines (Faria 2008).

Making a complete car and making a module of a car depending on car specifications are totally different considering synchronous production concept. To meet the customers' requirements, we just think of the numbers of produced cars according to the ordered types or options within a certain due date when we make complete cars. In this case, not only synchronism between parts and a car but also in-sequence delivery of parts is not critical. When we make a module of a car, however, we also need to consider shorter dues for synchronous production of each module, as well as the sequence of modules when they are delivered according to the option or specification of complete cars. Such constraints must be met by module suppliers.

2.2 *Modular assembly*

Sako (2003) claimed that the automotive industry is a source of innovative management practices for production in the twentieth century. He selected modular strategies in product design and production as a recent focus of many OEMs

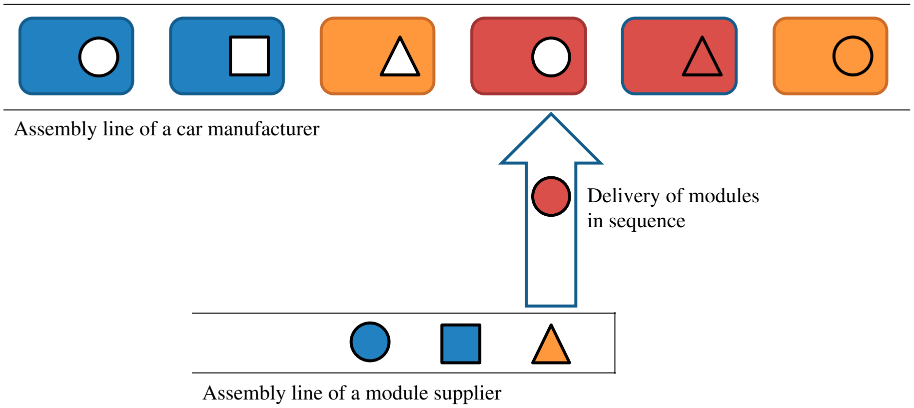


Figure 1. Assembly line of a car manufacturer and a module supplier.

and suppliers, and presented the next paradigm shift after Ford's moving assembly line and Toyota's Production System. Modularity in both product design and production is a major factor because it reflects the latest trend in simplifying and managing products under high-customisability requirements. As suggested by Bukchin, Darel, and Rubinovitz (1997), in the new design approaches of modern assembly systems, the long traditional assembly line is replaced by a modular, semi-autonomous assembly system based on shorter lines.

Sako and Murray (1999) reported that modularisation allows a large number of components to be pre-combined into modules on the factory floor. These modules can then be assembled off-line and brought onto the main assembly line, where they are incorporated through a small, simple series of tasks. As a motive for manufacturers to use modularity in their production processes, Baldwin and Clark (1997) reasoned that it has always been easier to produce complicated products by dividing the manufacturing process into process modules or cells. Sako (2003) identifies component interchangeability, late customisation and the resulting inventory reduction as sources of operational efficiency in modular production.

A modular assembly line has the following basic characteristics:

- Synchronous production of a module supplier when a customer call-off is realised
- Delivery of assembled modules in sequence within a given time frame
- Assembly facility located typically in close proximity to the customer production line due to the high transportation cost of the modules
- Assembly facility designed to respond to the maximum capacity of the customer
- Significant investment in information technologies to receive orders, manage material flow, enable module assembly and delivery
- Assembly line flexibility is crucial because the line is designed to respond to the maximum capacity requirements of the OEM, regardless of the average production rate

There are also potential benefits associated with modular production, such as 'stability in demand and supply patterns, inventory reduction, elimination of demand amplification and better long-term planning' (Andrian, Coronado, and Lyons 2008). On the other hand, module manufacturers face significant pressures because the entire vehicle assembly process depends on the timely delivery of defect-free parts to the final assembly line in the correct sequence (Larsson 2002). By utilising modularity, car manufacturers can shift some of their development and manufacturing responsibilities to their suppliers. This value shift in the automotive supply chain requires the performance of module suppliers to be above that of the car manufacturer itself and be improving continuously (Veloso and Kumar 2002).

3. Module assembly line concepts

3.1 *Conveyor line (CL)*

A conveyor system is mechanical handling equipment that moves materials from one location to another. The first module supplier addressed in this study uses the roller conveyor system in which the entire module is assembled. The CL is the most common production line concept and is used by many automotive manufacturers. In this process, the CL is divided into several assembly stations (see Figure 2). Each station contains components that must be assembled

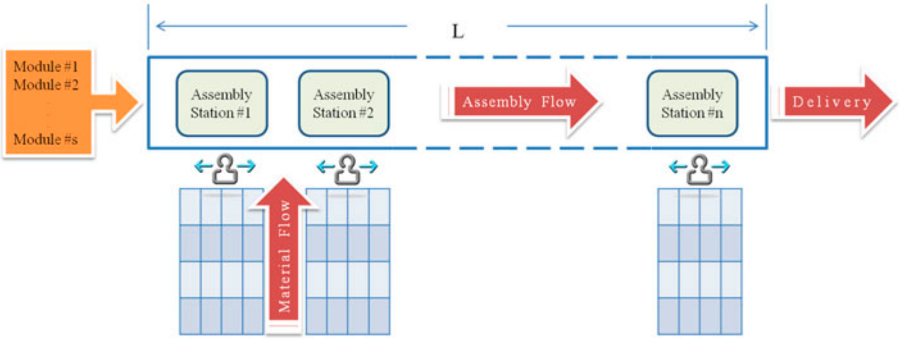


Figure 2. CL layout.

on the module. Component inventories are located next to the designated assembly station to minimise the distance travelled by labour to pick up a component. When the OEM realises the call-off, each assembly worker selects the related variant of the necessary component using the available assembly securing system. This system guides the worker to select the component's appropriate variant, which is determined by the manufacturing system for the specified module. The components are then assembled by the assembly worker as instructed by the manufacturing system. When the assembly work designated to that station is complete, the module is sent to the next station for the next round of parts assembly. This might not be the case in practice, but this study assumes one worker per assembly station (i.e. the manning level = 1). Part diversity assembled at each station creates product diversity. Therefore, this assembly concept can produce a range of different product models continuously in the same order, as requested by the customer, without requiring different models. Production is almost manual, and workers typically master the assembly work at their designated stations. Although the assembly work at each station differs slightly from one module variant to another, workers still benefit from learning effect due to repetition of similar tasks. The production inventory is stored behind the worker in shelves or racks. The location of the parts is arranged according to the use and component rate of each part assigned to be assembled at each station.

3.2 *Box assembly line (BAL)*

The BAL concept requires one worker to complete the entire module assembly work (see Figure 3). This manufacturing system does not provide module assembly or delivery sequences. As soon as the OEM performs the call-off, the logistics worker selects all the components needed to assemble the requested module variant from the shelves with the guidance of a picking system. These selected parts are gathered on a cart one by one. This cart is brought to an available assembly box when the process for selecting the parts is completed. If there is no box available at that moment, the parts are held at a waiting area until an assembly box is available. During this process, the call-off sequence can be

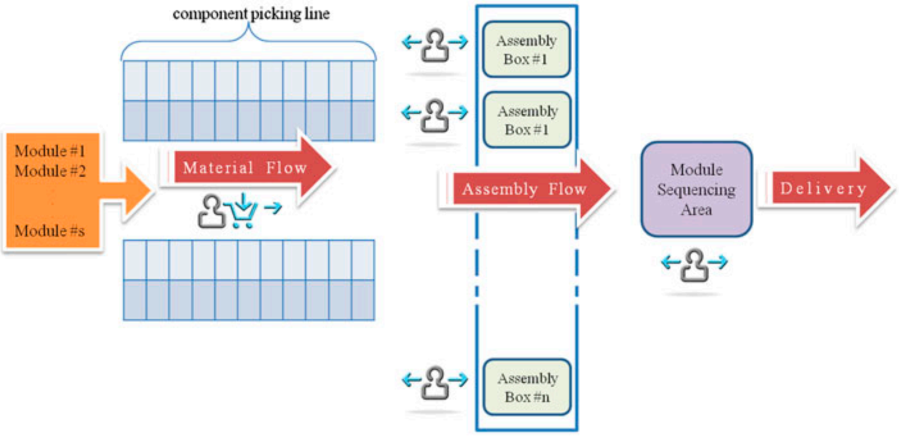


Figure 3. BAL layout.

disturbed. In the BAL concept, the whole assembly work is completed at a box by one labour. Afterwards, when module assembly is complete, final sequencing should be conducted to adjust the order of the module according to call-off order. Portions of the manufacturing process are manual and others are automated according to the process or technical requirements. The BAL concept has advantages and disadvantages over the CL. First, workers have a high level of responsibility because one worker performs all the main assembly work. Therefore, this manufacturing load requires more qualified workers. In addition, since the work scope confronted by one worker is bigger, the BAL concept offers less learning effect. Second, there is clear separation between part logistics and assembly operations. Third, modules are served by the available assembly box at the time they arrive because the sequence is not considered in assembly process. This process eliminates waiting and provides flexibility to the line. Additional labour is utilised to ensure that deliveries are completed in the correct sequence. Finally, the efforts of each worker can be evaluated.

4. Mathematical model

4.1 *Problem definition*

A module supplier may select one of the two assembly concepts mentioned in the previous section or any other assembly concept. This study assessed two different module suppliers that assemble front-end modules for two different vehicle manufacturers. One of the suppliers uses a CL due to process requirements and layout constraints. The other supplier uses the BAL concept because management perceives it to be more suitable for their operations. This study examined which line concept is more efficient by evaluating the productivity of the workforce in each assembly concept. To simplify the evaluation, some assumptions are made for each assembly concept. The analysis determines which line concept satisfies the given demand rate using a smaller amount of labour, where the demand rate refers to the number of modules per hour required by the OEM and are assembled by the module supplier.

The objective function for evaluating the two assembly concepts is defined as follows:

$$\text{Labour Productivity} = \text{Demand Rate}/\text{Total Number of Labour}[\text{unit: job per hour (jph)/labour}]$$

4.2 *Mathematical model for the CL*

For the CL, each component variant assembled at its designated assembly station should be considered part of the assembly work. Component variants differ in each module, which is defined by the OEM. The term, ‘component rate’, represents the frequency at which a component is assembled considering all the module variants demanded by the OEM. For example, if there are 100 module variants and component A is assembled on 60 of these modules, the component rate for component A is 60%. This definition is useful when calculating the average total work time spent on the assembly of one module. The following notations were used to define the total work time:

i	index of assembly stations $(1,2,\ldots,I)$
m	index of module variants $(1,2,\ldots\ldots,M)$
j	index of components $(1,2,\ldots\ldots,J)$
w_{ij}	assembly time of component j at station i (unit: minute)
p_{ij}	picking time of component j at station i (unit: minute)
u_{jm}	usage of component j in module m
r_m	rate of module variant m
d_c	distance between the CL and the part-picking location (unit: metre)
L	length of conveyor (unit: metre)
v_c	conveyor speed (unit: metre/minute)
M_i	manning level at station i
D	demand rate (unit: jph)

The following assumptions were made for the CL:

1. The CL is well balanced so that the total work time is shared more or less equally among stations.
2. The manning level of each station is one.
3. The total work time at any station is less than the demand rate to avoid waiting time between assembly stations.
4. Uniform sequence and uniform demand rate are available from the OEM.
5. The module supplier line has a uniform launch rate following the uniform demand rate of the OEM.

The cycle time of the CL is defined as the time that one module spends being processed or assembled. The cycle time includes both productive and non-productive time that an individual part spends at the machine (Groover 2008). The total work time for a module at a station is the sum of the total assembly time, the total time spent to select the related components at that station, and the sum of the total handling time that is spent to move a module from one station to another. A module variant requiring the longest total work time at that station needs to be considered when determining the cycle time.

TA_{im} and TP_{im} represent the assembly time and part-picking time, respectively, at station i for module m, and can be expressed as follows:

$$TA_{im} = \sum_{j=1}^{J} w_{ij} u_{jm} \tag{1}$$

$$TP_{im} = \sum_{j=1}^{J} p_{ij} u_{jm} \tag{2}$$

Since, the handling time of the module between the two stations must also be considered in the cycle time,

$$TH_{im} = \frac{L}{I v_c} \tag{3}$$

Finally, the total work time at station i for module m (TW_{im}) is represented in the following equation:

$$TW_{im} = TA_{im} + TP_{im} + TH_{im} \tag{4}$$

When the earlier equations are inserted into the formula,

$$TW_{im} = \left[\sum_{j=1}^{J} (w_{ij} + p_{ij}) u_{jm}\right] + \frac{L}{I v_c} \tag{5}$$

If a component is not to be assembled at station i, the corresponding part-picking time and assembly time are zero for this component at the station. When the entire assembly line is considered, the total work time spent to assemble one module is $[\sum_{i=1}^{I} \sum_{j=1}^{J} (w_{ij} + p_{ij}) u_{jm}] + \frac{L}{v_c}$. When all of the M module variants are considered, the formula becomes $\sum_{m=1}^{M} ([\sum_{i=1}^{I} \sum_{j=1}^{J} (w_{ij} + p_{ij}) u_{jm}] + \frac{L}{v_c})$.

The term component rate comes into the formulations at this point. The component rate can be used to determine the actual frequency of assembling component j in a module because the formulations need to consider whether component j is meant to be assembled for each variant.

The average total work time spent at assembly stations to produce one module can be expressed as Equation (6).

$$TW = \left[\sum_{i=1}^{I} \sum_{j=1}^{J} (w_{ij} + p_{ij}) u_{jm} r_m\right] + \frac{L}{v_c} \tag{6}$$

To satisfy the constraint of no waiting time, the number of assembly stations needs to be arranged, so the total work to be performed at one assembly station can be completed before the next module to be assembled arrives at that station. The time passing until the next module delivery to the station is equal to the launch rate. Therefore,

$$\frac{[\sum_{i=1}^{I} \sum_{j=1}^{J} (w_{ij} + p_{ij}) u_{jm} r_m] + \frac{L}{v_c}}{I} \le \text{launch rate} \tag{7}$$

where the launch rate is equal to $60/D$.

From Equation (7), the number of assembly stations is the minimum integer satisfying the equation.

Because the manning level at each station is assumed to be one, the total labour required to assemble one module is equal to the number of assembly stations. Therefore, the labour productivity can be formulated using Equations (8) and (9).

$$\text{Labour Productivity} = \frac{D}{\sum_{i=1}^{I} M_i} = \frac{D}{I} \tag{8}$$

By reorganising Equation (7),

$$\text{Labour Productivity} = \frac{D}{I} \leq \frac{60}{\left[\sum_{i=1}^{I}\sum_{j=1}^{J}(w_{ij}+p_{ij})u_{jm}r_m\right]+\frac{L}{v_c}} \tag{9}$$

This equation shows the maximum labour productivity achievable from the CL under given operating conditions and line assumptions.

4.3 *Mathematical model for the BAL*

For the BAL case, there is a fine line between the component picking operations and assembly operations. When a module order is available from the OEM, the corresponding components are first picked up from the shelves where the module parts are stored. These components are then brought to an available assembly box to be assembled. Therefore, the part-picking and assembly processes should be considered separate operations when calculating the total work time. Additional notations were defined to determine the total work time spent at this assembly line:

w_j	assembly time for component j (unit: minute)
p_j	picking time for component j (unit: minute)
d_b	average distance from picking line to assembly box (unit: metre)
v_w	labour walking speed (unit: metre/minute)
t	sequencing time per module (unit: minute)
M_p	manning level at picking line
M_a	manning level at assembly line
M_s	manning level at sequencing line

The assumptions for the BAL are as follows:

1. The manning level at each assembly box is one.
2. Uniform sequence and uniform demand rate are available from the OEM.
3. The module supplier line has a uniform launch rate following the uniform demand rate of the OEM.
4. Each module variant has the same sequencing time.

The total part-picking time for a module is $\sum_{j=1}^{J} p_j u_{jm}$. Then, the formula becomes $\sum_{m=1}^{M}\sum_{j=1}^{J} p_j u_{jm}$ for the entire demanded M number of modules. After all components are selected, they are brought to an available box assembly station for the module assembly job. The time spent for this transportation activity is defined as the handling time, and the required time for a trip per module is formulated as d_b/v_w. The total time spent for this transportation activity for M number of modules is $d_b M/v_w$. After the parts have been transported, the worker at the assembly box begins working on the module and spends an assembly time of $\sum_{j=1}^{J} w_j u_{jm}$ per module. The total time spent by all the workers to assemble M number of modules is $\sum_{m=1}^{M}\sum_{j=1}^{J} w_j u_{jm}$. After the assembly is complete, the modules are released for the sequencing job. Time t is spent per module to insert the module in the correct place in sequence.

If TP_m, TA_m and TS_m are defined as the cycle times of the picking line, assembly line and sequencing line for module m, respectively, then they can be formulated as follows:

$$TP_m = \sum_{j=1}^{J} p_j u_{jm} + \frac{d_b}{v_w} \tag{10}$$

$$TA_m = \sum_{j=1}^{J} w_j u_{jm} \tag{11}$$

$$TS_m = t \tag{12}$$

Therefore, the total work time (TW) for module m is

$$TW_m = TP_m + TA_m + TS_m \tag{13}$$

$$TW_m = \left[\sum_{j=1}^{J}(p_j + w_j)u_{jm}\right] + \frac{d_b}{v_w} + t \tag{14}$$

The average work time spent to produce one module using the component rate is

$$TW = \left[\sum_{j=1}^{J}(p_j + w_j)u_{jm}r_m\right] + \frac{d_b}{v_w} + t \tag{15}$$

The following constraints need to be met to satisfy the demand rate requirement D from the customer without any waiting time during the selection, assembly and sequencing processes:

$$M_p \geq \frac{TP}{\text{launch rate}} \tag{16}$$

$$M_a \geq \frac{TA}{\text{launch rate}} \tag{17}$$

$$M_s \geq \frac{TS}{\text{launch rate}} \tag{18}$$

where TP, TA and TS denote the cycle times of the picking line, assembly line and sequencing line, respectively.

From the above constraints, the manning level for each process is the minimum integer satisfying the above equations, where the launch rate is $60/D$. For the BAL, labour productivity is defined as the demand rate divided by the total labour:

$$\text{Labour Productivity} = \frac{D}{M_p + M_a + M_s} \tag{19}$$

By inserting Equations (13)–(18) into the above formula,

$$\text{Labour Productivity} = \frac{D}{M_p + M_a + M_s} \leq \frac{D}{\frac{TP+TA+TS}{\text{launch rate}}} \leq \frac{60}{\sum_{j=1}^{J}(p_j + w_j)u_{jm}r_m + \frac{d_b}{v_w} + t} \tag{20}$$

This equation shows the maximum labour productivity achievable from the BAL under given operating conditions and line assumptions.

4.4 *Comparison analysis*

The maximum possible labour productivity for the CL and BAL has been calculated as $\frac{60}{\sum_{i=1}^{I}\sum_{j=1}^{J}(w_{ij}+p_{ij})u_{jm}r_m+\frac{L}{v_c}}$ and $\frac{60}{\sum_{j=1}^{J}(p_j+w_j)u_{jm}r_m+\frac{d_b}{v_w}+t}$, respectively. By considering the same module demand package from the OEM for each line concept, the variants, use and rate of components to be assembled would be the same. Therefore, after neglecting the different positioning times of the two assembly line concepts, the total time to be spent selecting all the components and assembling these components on the modules would be the same. In other words,

$$\sum_{i=1}^{I}\sum_{j=1}^{J}(w_{ij} + p_{ij})u_{jm}r_m(\text{CL}) = \sum_{j=1}^{J}(p_j + w_j)u_{jm}r_m(\text{BAL}) = T, \quad \text{where } T \text{ is a positive number.} \tag{21}$$

If this constant is inserted into the labour productivity formulae,

$LP_{\text{CL}} = \frac{60}{T+\frac{L}{v_c}}$ and $LP_{\text{BAL}} = \frac{60}{T+\frac{d_b}{v_w}+t}$, where LP_{CL} and LP_{BAL} denotes the labour productivity of the CL and BAL, respectively.

From the above equations, the difference in the labour productivities of the two assembly line concepts is defined mainly by the layout characteristics of those concepts when considering the average assembly times of the demanded module. These two assembly line concepts were compared using a simulation, as reported in the next section.

5. Simulations

5.1 *Sample data*

Initially, sample data were created to simulate and compare the labour productivities of the two assembly line concepts. The data include front-end module demand information from the OEM, including component information to assemble this demand. The data introduced below are not fabricated completely but rather simplified, and are based on a previous study of two front-end module suppliers. To reduce the size of the simulation, several module variants are considered and the number of components is reduced. Only 34 components are involved in the assembly of this module concept, whereas in reality, this number can be in hundreds. Table 1 lists the complete list of components along with their usage and component rates with the respective selection and assembly times.

Four vehicle options related to the front-end module have been defined (see Table 2). The related vehicles were diversified according to their engine type, transmission type, air conditioner existence and market in which they are sold. By combining these four characteristics, a front-end module manufacturer can construct 16 different module variants, which should be assembled (see Table 3). The take rates for these modules are also defined in Table 3, showing the order frequency of each vehicle variant. Considering these module variants, Table 4 lists the component matrix, showing the components that should be assembled for each vehicle.

Both the CL and the BAL were designed to satisfy the customer demand rate given by the OEM. The demand rate (D) in this simulation was 15 jobs per hour. Table 5 lists the initial layout settings for the CL and BAL.

Table 1. Module components (unit: sec).

Component number	Component name	Component usage	Component rate (%)	Component work time	
				Picking	Assembly
1	Radiator gasoline	1	30	10	50
2	Radiator diesel	1	70	10	50
3	Mounting rubber	2	100	4	12
4	Radiator bracket	2	100	7	18
5	Airguide LH gasoline	1	30	7	18
6	Airguide LH diesel	1	70	7	18
7	Airguide RH gasoline	1	30	7	18
8	Airguide RH diesel	1	70	7	18
9	AT oil cooler	1	15	10	36
10	Condenser	1	80	10	48
11	Sealing foam	3	80	4	12
12	Intercooler	1	70	10	52
13	Intercooler hose	2	70	7	36
14	Hose clamp	4	70	4	38
15	Intercooler airguide LH	1	70	7	18
16	Intercooler airguide RH	1	70	7	18
17	Fan shroud gasoline	1	30	10	50
18	Fan shroud diesel	1	70	10	50
19	Screw M8	4	70	4	12
20	Bolt M8	3	70	4	12
21	Nut M8	3	70	4	12
22	Screw M6	4	30	4	12
23	Bolt M6	3	30	4	12
24	Nut M6	3	30	4	12
25	Headlamp LH	1	100	10	50
26	Headlamp RH	1	100	10	50
27	Headlamp bracket	2	100	4	18
28	Washer tank	1	100	10	36
29	Horn high DOM	1	35	7	20
30	Horn low DOM	1	35	7	20
31	Horn high EXP	1	65	7	20
32	Horn low EXP	1	65	7	20
33	Bumper beam	1	100	20	60
34	Front end carrier	1	100	20	60

Table 2. Vehicle variants.

Engine variant	Transmission variant	Air conditioner variant	Market variant
Diesel (DSL)	Automatic (AT)	With (WAC)	Domestic (DOM)
Gasoline (GAS)	Manual (MT)	Without (WOAC)	Export (EXP)

Table 3. Module variants.

Module number	Module rate (%)	Module variant			
1	9.8	DSL	AT	WAC	DOM
2	18.2	DSL	AT	WAC	EXP
3	2.5	DSL	AT	WOAC	DOM
4	4.6	DSL	AT	WOAC	EXP
5	9.8	DSL	MT	WAC	DOM
6	18.2	DSL	MT	WAC	EXP
7	2.5	DSL	MT	WOAC	DOM
8	4.6	DSL	MT	WOAC	EXP
9	4.2	GAS	AT	WAC	DOM
10	7.8	GAS	AT	WAC	EXP
11	1.1	GAS	AT	WOAC	DOM
12	2.0	GAS	AT	WOAC	EXP
13	4.2	GAS	MT	WAC	DOM
14	7.8	GAS	MT	WAC	EXP
15	1.1	GAS	MT	WOAC	DOM
16	2.0	GAS	MT	WOAC	EXP

5.2 *Experiment result*

After defining the input parameters, the total work time spent in each assembly line concept was calculated using Excel. First, the total work time needed to complete the assembly of each module variant under each assembly line concept was calculated. Tables 6 and 7 list the total work time for the CL and BAL, respectively. After the total work time was determined, the labour force needed to operate each line was calculated. Finally, the labour productivity of the lines was compared by calculating the output per unit of labour using the total work time and required amount of labour. Two module assembly lines were then designed and the results were verified by simulating a common demand on both line concepts.

5.2.1 *Excel calculation results*

Two results were calculated for a demand rate of 15 jobs per hour (jph). The first set of results was derived from the maximum work time, whereas the other was derived from the average work time using the component rate. Two productivity scales have been defined: the maximum achievable productivity and the actual productivity. The maximum achievable labour productivity refers to the capacity of the line concept when the utilisation rate is 100% and provides the number of modules that can be assembled by one unit of labour in one hour considering the work time of the modules. In contrast, the actual labour productivity refers to the real productivity that can be reached under current operating conditions and is calculated by the earlier labour productivity formula defined as the hourly demand rate divided by the amount of labour utilised. Table 8 lists the required labour headcount results for each assembly line concept.

The labour productivities of each line concept were calculated using the amount of labour required and the work times for each assembly line concept (see Table 9).

A maximum achievable labour productivity of 2.63 jph/labour was realised considering the maximum work time on the CL. The actual labour productivity was 2.50 jph/labour, which is similar to the maximum achievable labour productivity. Nevertheless, the maximum achievable labour productivity increased to 2.94 jph/labour when the average work time was considered, whereas the actual labour productivity was 2.50 jph/labour. This productivity evolution is due to the time difference between the maximum and average work times. According to the calculation results, six assembly

Table 4. Component matrix.

Component number	Component name	Engine	DSL	DSL	DSL	DSL	DSL	DSL	DSL	DSL	GAS	GAS	GAS	GAS	GAS	GAS	GAS	GAS
		Transmission	AT	AT	AT	AT	MT	MT	MT	MT	AT	AT	AT	AT	MT	MT	MT	MT
		Air Conditioner	WAC	WAC	WOAC	WOAC	WAC	WAC	WOAC	WOAC	WAC	WAC	WOAC	WOAC	WAC	WAC	WOAC	WOAC
		Market	DOM	EXP	DOM	EXP	DOM	EXP	DOM	EXP	DOM	EXP	DOM	EXP	DOM	EXP	DOM	EXP
		usage / module no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Radiator Gasoline	1									✓	✓	✓	✓	✓	✓	✓	✓
2	Radiator Diesel	1	✓	✓	✓	✓	✓	✓	✓	✓								
3	Mounting Rubber	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
4	Radiator Bracket	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
5	Airguide LH Gasoline	1									✓	✓	✓	✓	✓	✓	✓	✓
6	Airguide LH Diesel	1	✓	✓	✓	✓	✓	✓	✓	✓								
7	Airguide RH Gasoline	1									✓	✓	✓	✓	✓	✓	✓	✓
8	Airguide RH Diesel	1	✓	✓	✓	✓	✓	✓	✓	✓								
9	AT Oil Cooler	1	✓	✓	✓	✓					✓	✓	✓	✓				
10	Condenser	1	✓	✓			✓	✓			✓	✓			✓	✓		
11	Sealing Foam	3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12	Intercooler	1	✓	✓	✓	✓	✓	✓	✓	✓								
13	Intercooler Hose	2	✓	✓	✓	✓	✓	✓	✓	✓								
14	Hose Clamp	4	✓	✓	✓	✓	✓	✓	✓	✓								
15	Intercooler Airguide LH	1	✓	✓	✓	✓	✓	✓	✓	✓								
16	Intercooler Airguide RH	1	✓	✓	✓	✓	✓	✓	✓	✓								
17	Fan Shroud Gasoline	1									✓	✓	✓	✓	✓	✓	✓	✓
18	Fan Shroud Diesel	1	✓	✓	✓	✓	✓	✓	✓	✓								
19	Screw M8	4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
20	Bolt M8	3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
21	Nut M8	3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
22	Screw M6	4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
23	Bolt M6	3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
24	Nut M6	3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
25	Headlamp LH	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
26	Headlamp RH	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
27	Headlamp Bracket	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
28	Washer Tank	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
29	Horn High DOM	1	✓		✓		✓		✓		✓		✓		✓		✓	
30	Horn Low DOM	1	✓		✓		✓		✓		✓		✓		✓		✓	
31	Horn High EXP	1		✓		✓		✓		✓		✓		✓		✓		✓
32	Horn Low EXP	1		✓		✓		✓		✓		✓		✓		✓		✓
33	Bumper Beam	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
34	Front End Carrier	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 5. Module assembly line settings (CL and BAL).

CL		BAL	
Length of conveyor	40 m	Distance to assembly box	30 m
Conveyor speed	40 m/min	Labour walking speed	80 m/min

Table 6. Total work time for the CL (unit: sec).

Module number	Module rate (%)	Module variant				Picking time	Assembly time	Handling time	Total work time
1	9.8	DSL	AT	WAC	DOM	264	1044	60	1368
2	18.2	DSL	AT	WAC	EXP	264	1044	60	1368
3	2.5	DSL	AT	WOAC	DOM	242	960	60	1262
4	4.6	DSL	AT	WOAC	EXP	242	960	60	1262
5	9.8	DSL	MT	WAC	DOM	254	1008	60	1322
6	18.2	DSL	MT	WAC	EXP	254	1008	60	1322
7	2.5	DSL	MT	WOAC	DOM	232	924	60	1216
8	4.6	DSL	MT	WOAC	EXP	232	924	60	1216
9	4.2	GAS	AT	WAC	DOM	230	804	60	1094
10	7.8	GAS	AT	WAC	EXP	230	804	60	1094
11	1.1	GAS	AT	WOAC	DOM	208	720	60	988
12	2.0	GAS	AT	WOAC	EXP	208	720	60	988
13	4.2	GAS	MT	WAC	DOM	220	768	60	1048
14	7.8	GAS	MT	WAC	EXP	220	768	60	1048
15	1.1	GAS	MT	WOAC	DOM	198	684	60	942
16	2.0	GAS	MT	WOAC	EXP	198	684	60	942

Table 7. Total work time for the BAL (unit: sec).

Module number	Module rate (%)	Module variant				Picking time	Handling time	Assembly time	Sequencing time	Total work time
1	9.8	DSL	AT	WAC	DOM	264	23	1044	20	1351
2	18.2	DSL	AT	WAC	EXP	264	23	1044	20	1351
3	2.5	DSL	AT	WOAC	DOM	242	23	960	20	1245
4	4.6	DSL	AT	WOAC	EXP	242	23	960	20	1245
5	9.8	DSL	MT	WAC	DOM	254	23	1008	20	1305
6	18.2	DSL	MT	WAC	EXP	254	23	1008	20	1305
7	2.5	DSL	MT	WOAC	DOM	232	23	924	20	1199
8	4.6	DSL	MT	WOAC	EXP	232	23	924	20	1199
9	4.2	GAS	AT	WAC	DOM	230	23	804	20	1077
10	7.8	GAS	AT	WAC	EXP	230	23	804	20	1077
11	1.1	GAS	AT	WOAC	DOM	208	23	720	20	971
12	2.0	GAS	AT	WOAC	EXP	208	23	720	20	971
13	4.2	GAS	MT	WAC	DOM	220	23	768	20	1031
14	7.8	GAS	MT	WAC	EXP	220	23	768	20	1031
15	1.1	GAS	MT	WOAC	DOM	198	23	684	20	925
16	2.0	GAS	MT	WOAC	EXP	198	23	684	20	925

stations are needed to satisfy the module demand rate without any waiting time. Therefore, six units of labour are required because the manning level of the CL is one.

Two types of productivity results were also obtained for the BAL. Regarding the maximum work time calculations, the maximum achievable labour productivity obtained for the BAL was 2.67 jph/labour, whereas the actual labour productivity was only 1.88 jph/labour. The maximum achievable labour productivity increased to 2.98 jph/labour when the

Table 8. Labour headcount results.

	CL		BAL	
	Maximum work time	Average work time	Maximum work time	Average work time
Picking line	0	0	2	2
Assembly line	6	6	5	4
Sequencing line	0	0	1	1
Total labour headcount	6	6	8	7

Table 9. Productivity results.

	CL		BAL	
	Maximum work time	Average work time	Maximum work time	Average work time
Maximum achievable labour productivity	2.63	2.94	2.67	2.98
Actual labour productivity	2.50	2.50	1.88	2.14

calculations used the average work time, whereas the actual labour productivity increased to 2.14 jph/labour. These results are different from those for the CL. For the CL, only the maximum achievable labour productivity increased due to a change from the maximum work time to the average work time. With the BAL, both the maximum achievable labour productivity and the actual labour productivity increased because the amount of labour decreased with decreasing work time from the maximum work time to the average work time. When the maximum work time was considered, five assembly boxes were required to assemble the demanded modules without a waiting time. On the other hand, only four assembly boxes were required when the average work time was considered. Therefore, the actual productivity and maximum achievable productivity increased.

5.2.2 *Simulation results*

For building the simulation model in this study, we used the simulation language eM-Plant$^{\text{TM}}$ (Technomatix Technologies 2000). It is accepted as one of the few true object-oriented simulation packages that is commercially available (Law and Kelton 2000).

Three module assembly lines were designed to verify these findings by using eM-Plant$^{\text{TM}}$. The first line is a CL with six assembly stations (see Figure 4). Therefore, a total number of six workers were assigned to this line. The second line is a BAL with five assembly boxes (see Figure 5). Two additional workers were used for component handling and another worker was used for module sequencing. A total of eight workers were utilised in this line. The third module assembly line is a BAL with four assembly boxes. This line was designed to determine if fewer workers can manage the requested demand because the previous BAL calculations showed different labour requirements for the

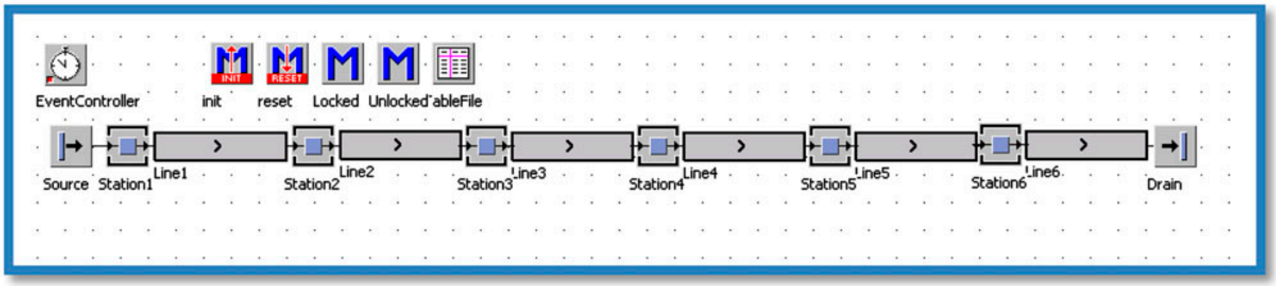


Figure 4. Simulation model for the CL.

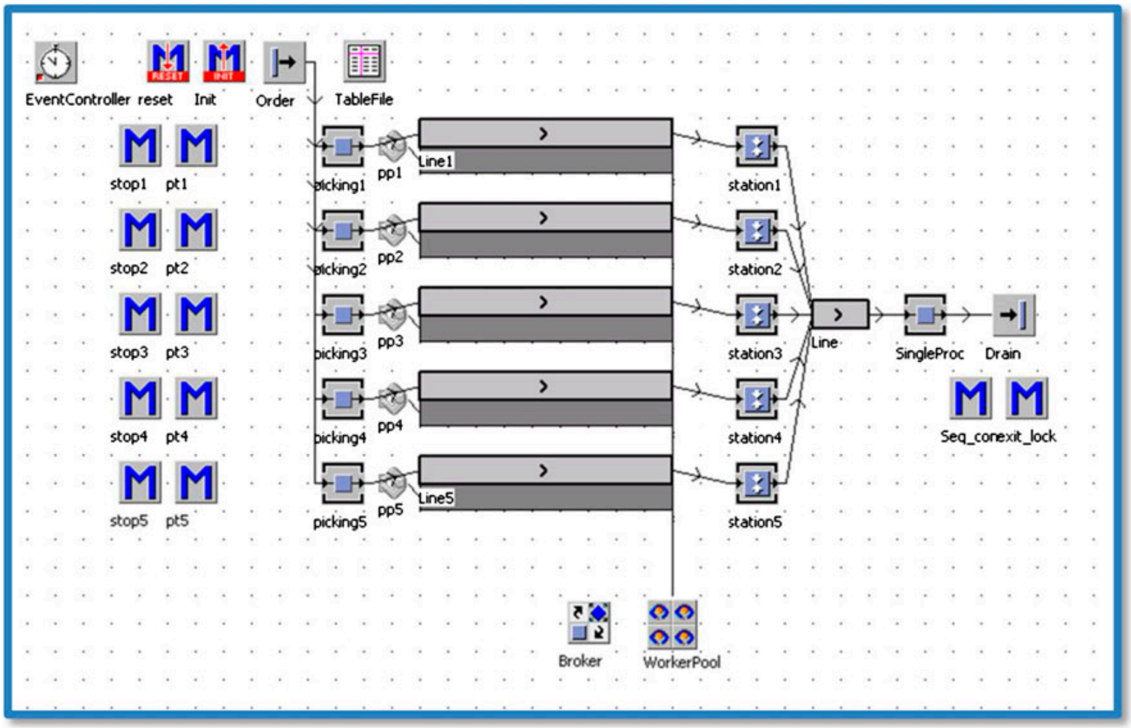
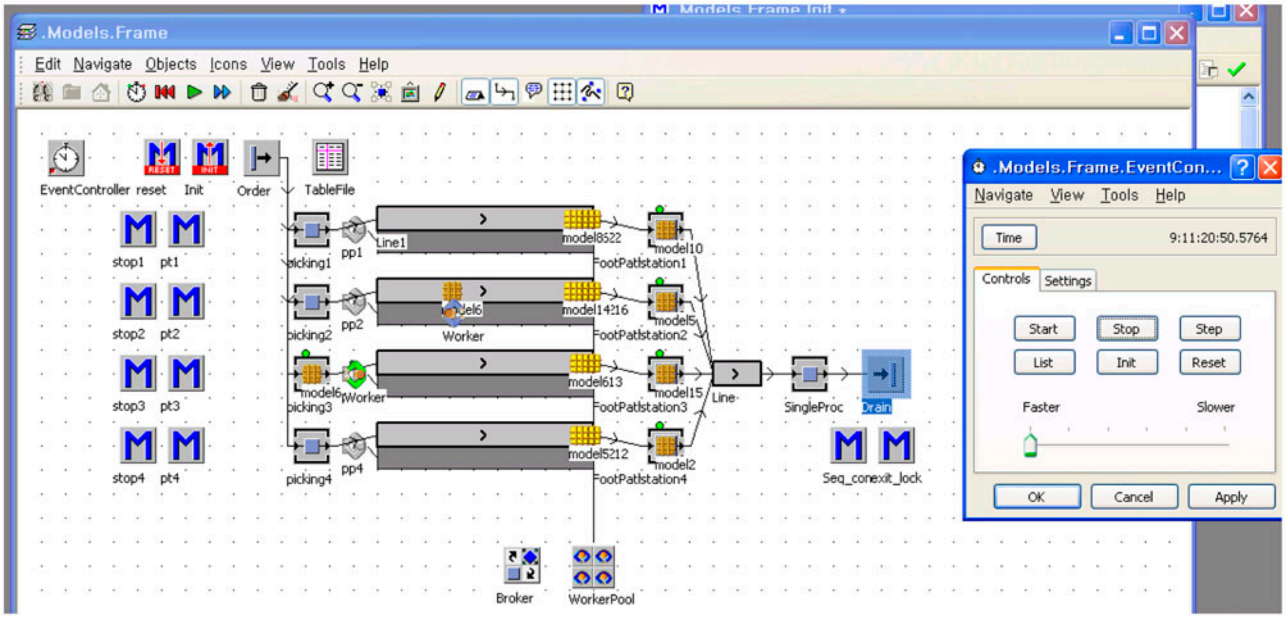


Figure 5. Simulation model for the BAL.

maximum and average work times. As in the previous BAL, this line utilises two workers for component handling and one worker for module sequencing. Therefore, a total of seven workers were needed in this line.

A common demand of 15 jph from the OEM was simulated for a continuous three shift/day operating condition over 15 consecutive days. In the CL simulation model, 'Source' icon creates 15 module orders per hour. These module orders are randomly generated using the module rates introduced in Table 3. Once the module orders are generated, they are brought to the first station in every 4 min. Since stations are assumed to be balanced perfectly, our simulation model simulates the same picking and assembly time at each station for the ordered module. Once the assembly work is completed at the station, the module is transferred to the next station through conveyor. In the BAL simulation model, module ordering process is same as in the CL. Note that 'Order' icon in the BAL simulation model functions as same as 'Source' icon in the CL model. When a module order arrives at 'Picking', a worker is dispatched from 'WorkerPool' to realise picking process according to the respective picking time of the ordered module. If there is no worker available in the 'WorkerPool', no more assembly process can be performed and some waiting time occurs. After picking processes are complete, the worker brings the components to an available 'Station'. Then, the worker returns back to the 'WorkerPool'. Meanwhile, an assembly worker is dispatched to the 'Station' to do the module assembly work. This worker assembles the module according to the time required for the ordered module as shown in Table 3. After assembly work is complete, the module arrives at 'SingleProc' where it is placed in the correct sequence mentioned in the order list. A similar module work time was experienced for the first and second assembly lines. The work times in the simulation are slightly shorter because the simulation allows the operators to begin working on the next module once the current module assembly is completed at the station. Therefore, when modules require less work time than the average or maximum work times, the next module can arrive at the assembly station earlier and be assembled earlier. On the other hand, in the third assembly line, waiting queues occur in front of the assembly boxes (see Figure 6). Overall, the total work times for the modules were significantly higher than the calculation results because four assembly boxes were designed based on the average module work times. Therefore, the arrival of a module requiring a longer work time than the average work time can delay the overall assembly operation in that box, which can lead to an increasing number of modules waiting in the queue.



Time 9:11:20:50.5764

Figure 6. Simulation screenshot showing queuing at the BAL (four assembly boxes).

6. Conclusions

Two module assembly line concepts, used by suppliers in the automotive industry, were analysed by developing their corresponding mathematical models. In fact, there are also different production line concepts studied in literature, such as part kitting as in the case of the BAL and vehicle assembly as a mix of BAL and CL (Engström, Jonsson, and Medbo 1998). In their study, a layout was proposed, which consists of part kitting for material handling and a parallel flow for vehicle assembly where operators assembled one-quarter of the vehicle. However, as stated in their paper as well, if the product sequence is locked, the major benefits of parallelisation are lost. The modular production or assembly considered in this paper is distinctively differentiated with previous literature in a fact that synchronous production and in-sequence delivery are mandatory. The respective labour productivities of above-mentioned two module assembly line concepts were compared as a performance measure. Both Excel calculations and simulations on numerical examples were used to perform this comparison. The results revealed similar maximum achievable productivities in the CL and BAL. Nevertheless, the CL showed better actual productivity than the BAL. This study has shown that the CL concept is preferable over the BAL under modular production environment, assuming that the CL is perfectly balanced.

The maximum achievable productivities are similar because the CL and BAL face similar work times. The work time in the BAL is higher due to the additional module sequencing activity. In the CL, this additional sequencing time is not required due to a line characteristic enabling sequential assembly. Part handling work takes less time in the BAL because the layout of the concept enables components to be stored in two parallel lines. The actual productivity difference between the two assembly line concepts can be explained by deviations in the total amount of labours utilised. This has two explanations. First, in the BAL, the additional module sequencing can only be performed by one dedicated person. At this point, delivery of the assembled modules may be taken into consideration. This job may require additional labour depending on the delivery method. If this is the case, job sharing can be achieved in the BAL by combining the sequencing and delivery operations. This type of synergy would clearly improve the actual labour productivity. The deviation in the actual labour productivity is also due to the job sharing opportunity between workers in the CL. The CL enables assembly workers to handle both component selection and assembly operations. In contrast, the BAL draws a clear line between picking and assembly operations, as well as the sequencing operation. This clear role separation restricts job sharing between workers and disables synergy opportunities. For example, when the productivity of each worker was analysed, the productivities of the component selection and sequencing were found to be low. In the BAL, two workers are assigned to component selection and one worker is assigned to sequencing. Nevertheless, the job being performed by these three workers can be completed by two workers if job sharing is allowed.

This study did not allow any waiting time for the sake of simplicity. The results for both line concepts might be different if a predefined waiting time is allowed. Because the BAL has more buffer opportunities due to its layout characteristics, it is highly likely that more improvement would be experienced in the BAL than in the CL if sufficient waiting time is allowed. In addition, it was assumed that the balance efficiency of the CL was perfect and the workload was shared equally between stations, allowing an equal manning level. Throughput and efficiency of the CL depends on the degree of balance between stations (Sengupta and Jacobs 2004). Labour productivity would decrease if the balance efficiency is lower. Future research should investigate the degree of balance inefficiency that would result in an actual productivity worse than the BAL offers. Furthermore, learning effect was ignored while designing assembly stations in this study. Since assembly work is divided per station in the CL, work scope per labour is less when compared with the BAL. Note that one worker performs all the main assembly work in the BAL, whereas the same assembly work is shared by several workers in the CL. This gives two advantages to the workers assembling in the CL concept. First, these workers in the CL have less work to learn, which speeds up their learning process. Second, since their workload is less, they have more opportunity, i.e. work frequency is higher, to repeat the same activity in one shift. This division of labour and the resulting specialisation can make the CL very efficient (Ghosh and Gagnon 1989). As a result, we can expect a higher learning index in the CL concept. Therefore, learning effect would increase the labour productivity gap between the CL and BAL in favour of the CL.

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